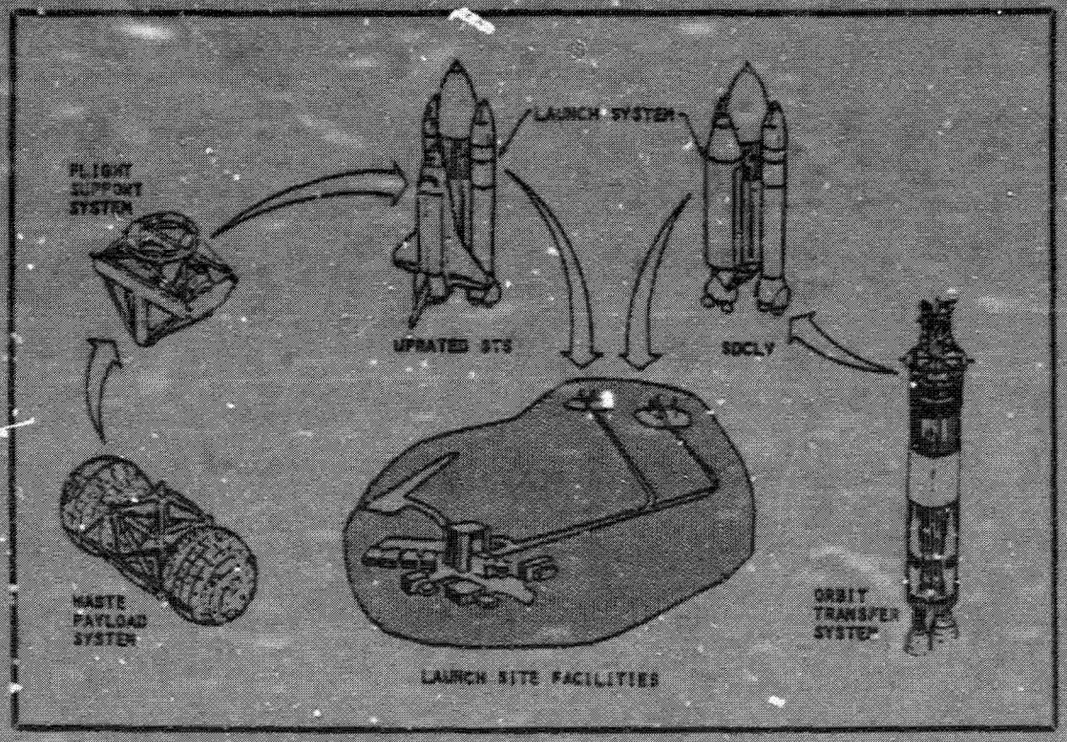
ANALYSIS OF SPACE SYSTEMS FOR THE SPACE DISPOSAL OF NUCLEAR WASTE FOLLOW-ON STUDY



STUDY REPORT-VOLUME 1

EXECUTIVE SUMMARY

1982

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THE BOEING COMPANY

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EXECUTIVE SUMMARY

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Submitted to

The National Aeronautics and Space Administration

George C. Marshall Space Flight Center

by

Boeing Aerospace Company

Seattle, Washington 981244

FOREWORD

This Boeing Aerospace Company (BAC) study is an integral part of the ongoing DOE-NASA program for the study of nuclear waste disposal in space, managed by the Office of Nuclear Waste Isolation (ONWI). The research effort reported here was performed from June of 1981 until February of 1982 by the BAC Upper Stages and Launch Vehicles organization as a follow-on effort to NASA contract NAS8-33847. The objective of the follow-on study was to define the major impacts on the space system concepts selected in the 1980 study that would result from changes in the reference nuclear waste mix from the PW-4b mix used in the 1980 study.

Information developed during the study period is contained in this two-volume final report as listed below:

Volume 1 Executive Summary
Volume 2 Technical Report

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1.0 INTRODUCTION

Since 1970, a number of concepts for the space disposal of nuclear waste have been studied and evaluated. This study evaluated the impact on space systems of three alternative waste mixes. This effort is an integral part of the ongoing NASA-DOE program to evaluate the disposal of certain high-level nuclear wastes in space as a complement to mined geologic repositories. This introduction provides a brief overview of the study background, objectives, scope, approach and guidelines, and limitations.

1.1 BACKGROUND

NASA and DOE are conducting a sustaining-level assessment of concepts for nuclear waste disposal in space. The 1980 MSFC-Boeing study of space systems for space disposal of nuclear wastes (contract NAS8-33847) investigated reasonable alternative concepts (space transportation systems, payload protection systems, and space destinations) to dispose of the current reference nuclear waste (Purex PW-4b waste mix in cermet form). That study resulted in selection of several alternative concepts warranting further indepth study and evaluation.

The follow-on effort described in this report emphasized the effects of variations in waste mixes on space system concepts in order to provide data for determining relative total system risk benefits resulting from space disposal of the alternative waste mixes.

1.2 OBJECTIVES

Overall objectives of the NASA-DOE sustaining-level study program are (1) to investigate space disposal concepts which will provide information to support future nuclear waste terminal storage (NWTS) programmatic decisions and (2) to maintain a low level of research activity in this area to provide a baseline for future development should a decision be made to increase the emphasis on this option.

The specific objective of this follow-on study was to define major impacts on the reference space system concepts that would result from changes in the nuclear waste mix from the PW-4b mix stated in the 1980 study.

To accomplish this objective, the study was divided into four major areas, each having its own objectives, as follows:

Task 1. Characterization of alternative waste forms (sec. 2.1):

1. Identification of waste form parameters relevant to the design of waste payloads for space disposal systems
2. Evaluation of identified parameters
3. Characterization of waste form dimensional and manufacturing-imposed limits

Task 2. Determination of impact on waste payload systems (sec. 2.2):

1. Identification of waste payload concepts compatible with the alternative waste forms identified in task 1
2. Characterization of identified concepts over a range of masses compatible with alternative space transportation systems under consideration

Task 3. Determination of impact on space transportation systems (sec. 2.3):

1. Determination of the optimum launch system for alternative low-launch-rate systems
2. Definition and characterization of candidate orbit transfer systems compatible with the optimum launch systems
3. Integration of launch system and orbit transfer system characteristics with waste payload characteristics (defined in task 2) to determine relative performance of alternative total system concepts

Task 4. Determination of characteristics of reference space system (sec 2.4):

1. Determination of system element characteristics
2. Definition of system operations to the level required to support system risk estimates

1.3 SCOPE

The study was conducted over a 9-month contract period, divided into a 7-month technical effort followed by 2 months for preparation and delivery of the final report. The study effort was sufficient to (1) scope the full range of parameters characteristic of alternative waste payloads and (2) assess the impact on alternative space systems to a level sufficient to allow comparison with the existing reference system and alternatives

defined in the current study in the areas of technical feasibility, reliability, and long-term risk. Maximum use was made of past and current studies and other data appropriate to restrict additional analyses and definition to those areas specific to the study.

The reference space system selected at the first working-group meeting was defined in terms of major elements and operations to support concurrent analyses of space system risk.

1.4 APPROACH AND GUIDELINES

The overall approach used in conducting this study is illustrated schematically in Figure 1.4-1. Tasks are shown in the approximate order in which they were accomplished.

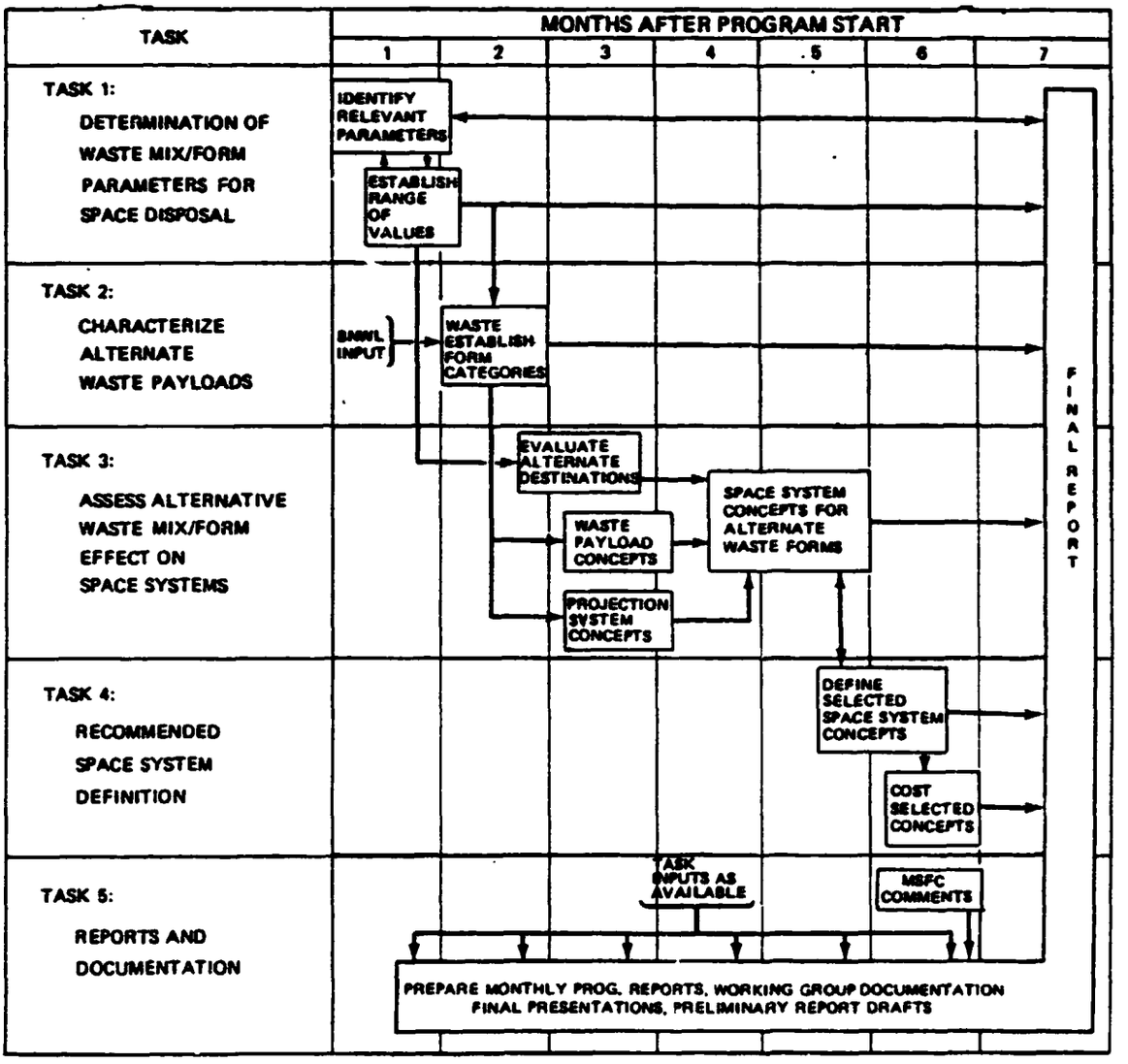

Figure 1.4-1. Overall Approach and Task Interrelationships

In task 1, conducted in the first month of the study, parameters relevant to nuclear waste payload design were identified and their values established. The results of this task allowed definition of alternative waste forms in task 2, which allowed identification and characterization of waste payload concepts for each waste mix/form. In task 3, the effects of these waste payloads on the space transportation systems required for space disposal were evaluated and space system concepts for the waste mixes were identified. A review of these concepts at the first working-group meeting allowed selection of a reference concept for space disposal. In task 4, the selected space system was defined to the level required to support concurrent estimates of total system risk. The results of all four tasks were used in task 5 to prepare monthly progress reports, working-group briefings, final briefings, and this final report.

Significant study guidelines and assumptions are as follows:

1. Maximum use was made of past studies and data as appropriate.
2. Characteristics of the space systems considered were derived from the concepts identified in the 1980 MSFC-Boeing study.
3. Definition of the waste mixes and forms was obtained from a parallel study by Battelle Northwest Laboratories.
4. System safety guidelines used in the reference space system design were derived from a parallel study by Battelle Columbus Laboratories.
5. Thermal loading of waste forms was low enough to prevent post-burial meltdown. (Burial can result from an accident-induced payload-ground impact.)
6. No liquid or powder states were considered for the waste forms.
7. Estimates of waste form quantity for defining space system flight rates were based on a 4480-MTHM/year rate of high-level waste generation.
8. Only the circular heliocentric orbit at 0.85 AU was considered as a space disposal destination.
9. The shield configuration from the 1980 study was used for all waste payloads and waste forms.

1.5 STUDY LIMITATIONS

Due to time and budget constraints, this study was restricted to consideration of a single waste payload shield configuration even though design constraints imposed by the alternative waste mixes are sufficiently different to require significantly different shield designs for each waste mix.

While these differences are not sufficient to perturb the results of this study, further consideration of the identified waste forms should begin with a reinvestigation of shield design aimed at providing an optimum shield configuration for each waste mix.

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2.0 SUMMARY OF KEY FINDINGS

Principal findings of this study are reported here for the four major task areas. The sequence of these findings is in logical progression, beginning with characterization of alternative waste mixes/forms.

2.1 CHARACTERIZATION OF ALTERNATIVE WASTE FORMS

Primary issues in this area were identification of parameters relevant to the design of space disposal systems and determination of their values.

Parameter Identification. Parameters, shown in Figure 2.1-1 with relevant mission areas specified, were identified in six primary areas: nuclear, strength of materials,

AREA	PARAMETER	WASTE MIX/FORM TYPE		
		$Pb\ I_2^{129}$	Tc^{99}	MOD. MLW IN ORNL CERMET
NUCLEAR	QUANTITY (kg /MTHM)	0.40	0.75	47.38
	TYPE OF NUCLEAR RADIATION EMI. ED	LOW ENERGY β-0 0.189 mev	LOW ENERGY β-0 0.292 mev 6.2×10^{8} $\frac{dis}{g\text{-}sec}$	HIGH ENERGY $\bar{\gamma}$ η 0 13 mev
	HALF LIFE (YEARS)	1.7×10^{7}	2.12×10^{5}	VARIES
CHEMICAL OR CRYSTAL STRUCTURE	CHEMICAL STABILITY	RELATIVELY INERT	TARNISHES IN MOIST AIR	SOME OXIDATION
	WASTE FORM LOADING $\left(\frac{kg\ ISOTOPE}{kg\ WASTE\ FORM}\right)$	0.56	1.00	0.61
MECHANICAL	DENSITY (g/cm^3) THEORETICAL/NET (1)	6.16 / 5.56 (AS CAST)	11.50/10.93 (BILLET)	6.50/6.50 (BILLET)
	MELTING POINT (°C)	402	2172	1200 (2)
	BOILING POINT (°C)	832	4827	NA
	COEFFICIENT OF LINEAR EXPANSION (10^{-6}/°C)	(3)	(3)	16.0
STRENGTH OF MATERIALS	ULTIMATE TENSILE STRENGTH OR MODULUS OF RUPTURE (Pa)	(3)	(3)	6.93×10^{8} (4)(5)
	YIELD STRENGTH IN COMPRESSION (0.2%OFFSET) (Pa)	(3)	(3)	3.38×10^{8} (4)(5)
	YIELD STRENGTH IN TENSION (0.2%OFFSET) (Pa)	(3)	(3)	3.19×10^{8}
	POISSON'S RATIO	(3)	309(4)	0.29-0 33
	YOUNG'S MODULUS (Pa)	(3)	3.22×10^{11}(4)	1.92×10^{11}(4)(5)
THERMAL	THERMAL LOADING (w/kg)	6×10^{-5}	1.2×10^{-2}	1.00
	THERMAL CONDUCTIVITY $\left(\frac{w}{m\text{-}°C}\right)$	(3)	5.0	9.5
	SPECIFIC HEAT (CAL/g.°C)	0.04	0.058	0.14
MANUFACTURING	HANDLING AND ASSEMBLY	GLOVE BOX	GLOVE BOX	REMOTE ONLY
	FABRICATION	CASTABLE IN PLACE	POWDER METALLURGY UNIAXIAL PRESS SINTER 1.0 DIA./LENGTH 60cm MAX DIM.	POWDER METALLURGY UNIAXIAL PRESS AND SINTER 1.0 DIA./LENGTH 60cm MAX DIM.

NOTES: (1) INCLUDES EFFECT OF POROSITY, VOIDS, INCLUSIONS
(2) FABRICATION TEMPERATURE
(3) DATA UNAVAILABLE IN LITERATURE: RESEARCH REQUIRED
(4) VALUE MEASURED AT ROOM TEMPERATURE
(5) SOLUTION HEAT TREATED

Figure 2.1-1. Definition of Parameter Values for Candidate Waste Mixes/Forms

mechanical, thermal, manufacturing, and chemical or crystal structure. Parameters were evaluated for their relevance to mission areas of risk, flight rate, and waste payload design. Emphasis was placed on identifying parameters relevant to risk and flight rate. Fabrication parameters were identified as a consequence of risk, flight rate, and as

required for the level of detail necessary for waste payload concept definition in task 4. This effort provided a guide to the relative importance of evaluating the identified parameters.

Parameter Values. Values of the parameters are also shown in the figure and areas are noted where further research is required. Ranges for the values can be determined by inspecting the figure.

Waste Form Configurations. Two basic configurations were defined for the three candidate waste forms. These configurations are illustrated in Figure 2.1-2. Configurations were designed to conform to the waste form physical and mechanical properties identified in the previous task.

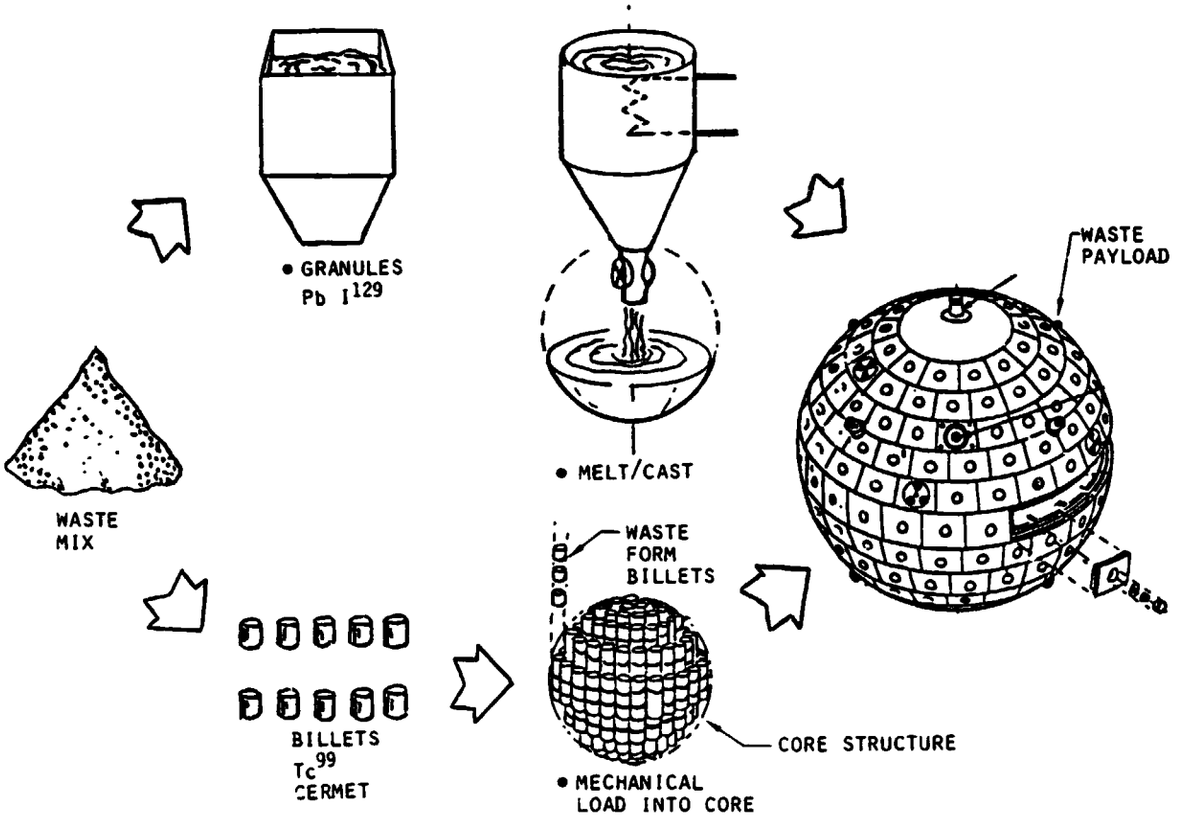

Figure 2.1-2. Candidate Waste Form Configurations

The technetium and cermet waste forms are fabricated as right cylindrical billets with height equal to diameter. Corners are rounded to accommodate the uniaxial press and sintering process used for fabrication. Size of individual billets is limited by constraints imposed by the fabrication process to approximately 50 mm maximum dimension (height or diameter). Several thousand of the technetium or cermet billets are stacked in a hexagonal, closed-packed array for maximum volumetric efficiency in

packing the spherical radiation shield and primary container. The exact size and number of billets are selected as functions of payload size to maximize payload density. The lead iodide waste form used for disposal of iodine 129 is melted and cast in place within the spherical radiation shield and primary container to yield a monolithic, spherical waste form. Although, theoretically, 100% volumetric efficiency could be approached using this method, a more conservative 90% efficiency was assumed to allow for voids and shrinkage during the casting process.

2.2 IMPACT ON WASTE PAYLOAD SYSTEMS

Candidate waste payload configurations designed to accommodate the three alternative waste forms are shown in Figure 2.2-1. Both configurations use the shield concept

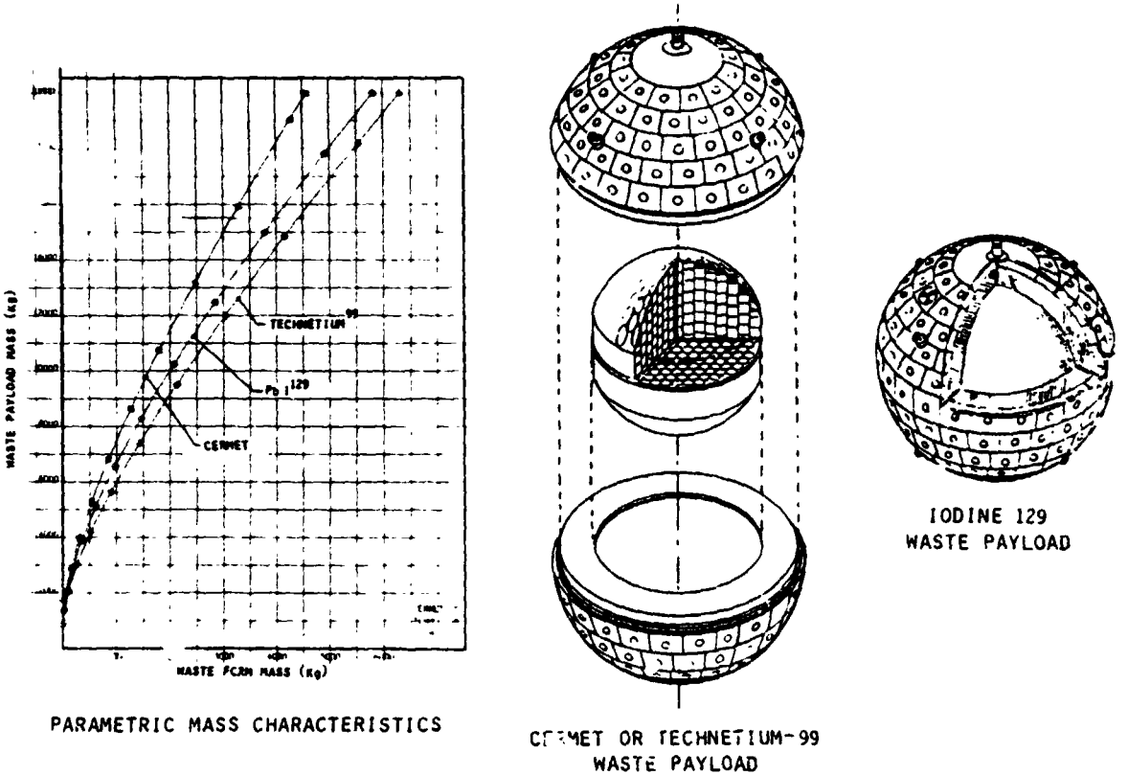

Figure 2.2-1. Characterization of Waste Payloads for Alternative Waste Forms

developed in the MSFC-Boeing 1980 study. The shield assembly is the primary barrier against waste form release, encasing the core and waste form billets in a seamless shell of 224-mm-thick Inconel 625 superalloy. This shell is further protected by a layer of graphite in the form of 220 interlocking tiles, 50 mm thick, and a final 4.3-mm-thick outer steel shell. The technetium or cermet waste form billets are stacked in bores drilled in a solid stainless steel waste form support structure (or core). The shield

assembly is fabricated in two halves, which are assembled around the core and electron-beam welded into a single seamless unit. In contrast, the iodine 129 waste form is cast in place inside an assembled spherical shield. The molten lead iodide is poured in through a small aperture that is welded shut following casting. Closeout tiles are installed over the weld plug in the metal shield.

Figure 2.2-1 also shows the ratio of total waste payload mass to the mass of waste form delivered for the three candidate waste forms. Technetium 99 is the most efficient due to its density. Lead iodide is the second most efficient due to the high volumetric efficiency of the cast-in-place method of waste payload fabrication. Cermet's relatively low density and the inherent reduction in volumetric efficiency due to stacking of the cylindrical billets result in the cermet waste form showing the least packing efficiency of the three waste forms.

These characterizations, relating delivered waste form mass to gross waste payload mass, were the basis for later total space system performance estimates.

2.3 IMPACT ON SPACE TRANSPORTATION SYSTEMS

Determining the impact on space transportation systems required resolution of three primary issues:

1. Which launch systems offer the best combinations of cost, risk, and availability for the alternative candidate waste forms requiring drastically reduced launch rates?
2. Which orbit transfer system options are most capable of performing the space disposal mission for alternative waste mixes when used with the selected 65K space transportation system (STS)?
3. Which combinations of orbit transfer, launch, and waste payload systems offer the best combinations of performance and risk?

Launch System Selection. Candidate launch systems were identified in the 1980 MSFC-Boeing study. Figure 2.3-1 compares launch system life cycle costs and shows some key assumptions used in their calculation. The ordinate shows estimated launch system life cycle costs in billions of dollars. Cumulative mass in thousands of metric tons is plotted on the abscissa, along with years from program start for the reference mission scenario.

Launch costs for the candidate systems are represented by the four lines running from left to right. The slope intercept represents the initial investment for design, development, test, and evaluation (DDT&E). Values range from zero for the reference

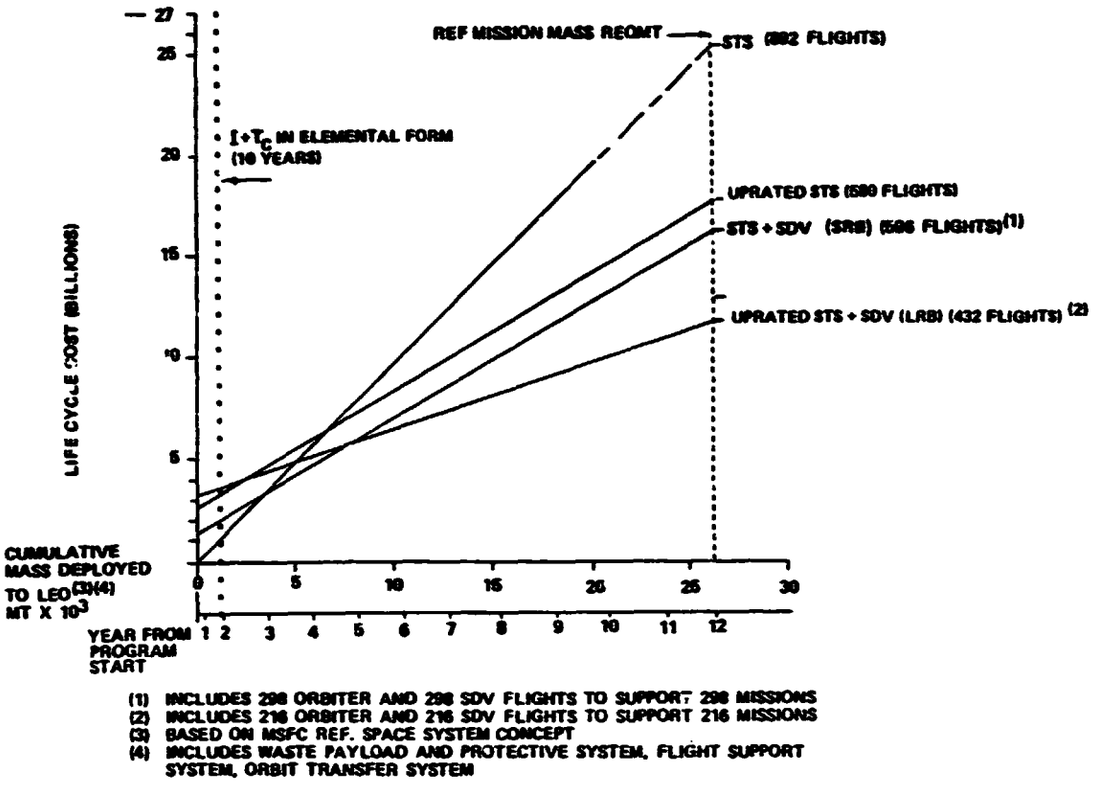
REF MISSION MASS REQMT
STS (992 FLIGHTS)
I+T$_C$ IN ELEMENTAL FORM (10 YEARS)
UPRATED STS (589 FLIGHTS)
STS + SDV (SRB) (586 FLIGHTS)(1)
UPRATED STS + SDV (LRB) (432 FLIGHTS) (2)
LIFE CYCLE COST (BILLIONS)
CUMULATIVE MASS DEPLOYED TO LEO(3)(4) MT X 10^3
YEAR FROM PROGRAM START
(1) INCLUDES 298 ORBITER AND 298 SDV FLIGHTS TO SUPPORT 298 MISSIONS
(2) INCLUDES 216 ORBITER AND 216 SDV FLIGHTS TO SUPPORT 216 MISSIONS
(3) BASED ON MSFC REF. SPACE SYSTEM CONCEPT
(4) INCLUDES WASTE PAYLOAD AND PROTECTIVE SYSTEM, FLIGHT SUPPORT SYSTEM, ORBIT TRANSFER SYSTEM

Figure 2.3-1. Life Cycle Cost Comparison for Candidate Launch Vehicles

STS to about $3.2 billion for the uprated STS, teamed with the liquid rocket booster version of the shuttle-derived cargo launch vehicle. The slope of each line is proportional to the cost per fight.

Vertical dotted lines represent the cermet mass transported to low Earth orbit (LEO) for the reference mission (approximately 27,000t over 10 years) and the sum of both iodine 129 and technetium (approximately 2,000t over 10 years).

The choice of the most cost-effective launch system for both cermet and technetium plus iodine waste forms is apparent. The combination of uprated STS plus shuttle-derived vehicle is the most cost effective for the high launch rate required by the cermet waste payload, showing cost savings of approximately $4 billion over the next most cost-effective system. At the low launch rate required by the iodine and technetium waste forms, the existing 65K STS is the most effective choice, showing total costs of $1 billion less than the cost of the next most effective candidate. This cost savings is due in large part to elimination of DDT&E expenses made possible by use of an existing system. The risk advantages of the winged orbiter are retained.

Orbit Transfer System Evaluation. Candidate orbit transfer systems compatible with the 65K STS are shown in Figure 2.3-2 with a summary of their performance

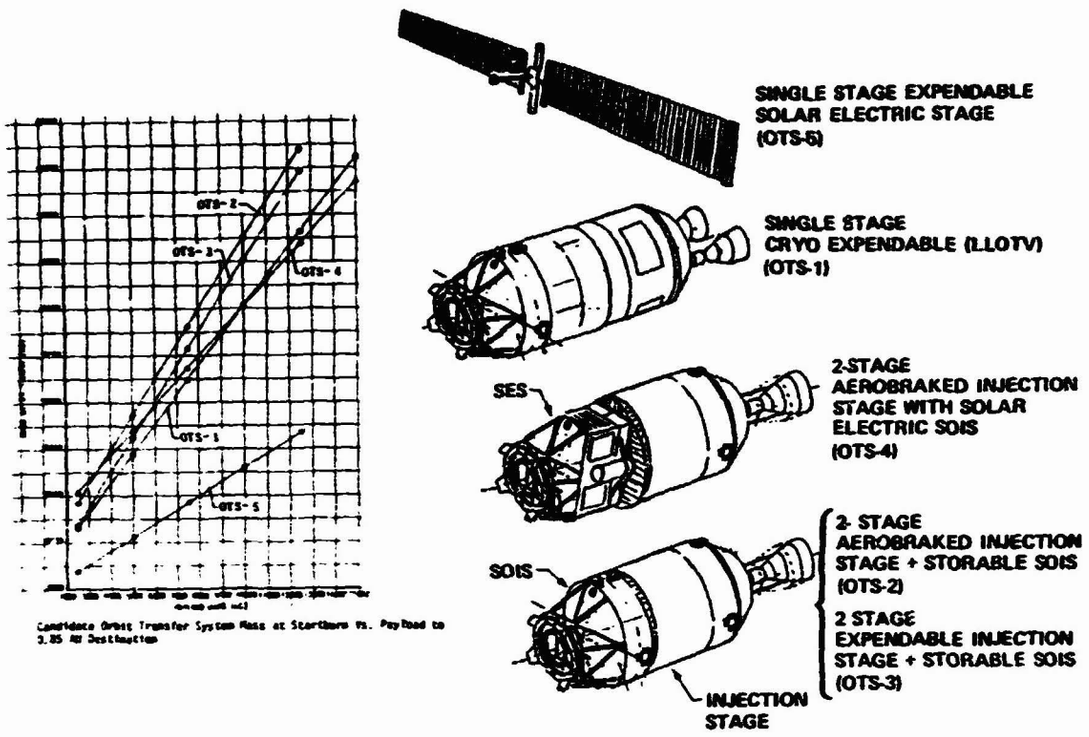

Figure 2.3-2. Characterization of Selected Orbit Transfer Systems

characteristics. Selected vehicles include a single-stage expendable solar electric stage, a single-stage expendable cryogenic propellant stage, a two-stage aerobraked reusable injection stage with a solar electric solar orbit insertion stage (SOIS), and two two-stage systems using storable propellant SOIS's, one with an expendable and one with a reusable cryogenic propellant insertion stage. The accompanying plot illustrates performance of the candidate systems. Orbit transfer system mass is plotted on the ordinate as a function of delivered payload mass, plotted on the abscissa. Variables include both solar electric and storable propulsion and two injection-stage options. The mass at startburn of each system can be determined for any waste payload mass between 2500 and 15,000 kg. These performance characteristics were used with the waste payload and launch vehicle characteristics as the basis for the total system performance comparisons.

Total System Evaluation. A total of 10 distinct transportation concepts for space disposal of low-launch-rate waste forms can be formed by combining one of two launch systems with one of five orbit transfer systems. One orbit transfer system option has been eliminated because of its incompatibility with the dual-launch system, yielding a total of nine candidate space transportation systems. Any of these could be used to dispose of either of the low-launch-rate waste mixes, yielding a total of 18 alternative concepts.

The 18 concepts were evaluated for performance using techniques which allow direct and simultaneous graphic comparison of total system performance by combining parametric characterization of orbit transfer system performance and waste payload systems. Results are summarized in Figure 2.3-3. The performance of low-launch-rate systems using one or two launches of the 65K STS with various orbit transfer systems is shown in terms of delivered waste form mass and equivalent flights per year for each candidate system. Performance of the system described in section 2.4 for the cermet waste form is shown for reference. The five systems shown were selected from the 18 candidates on the basis of performance.

	LAUNCH SYSTEM	ORBIT TRANSFER SYSTEM CODE *	TOTAL SYSTEM OPTION	NET PAYLOAD MASS/MISSION (Kg)	WASTE FORM MASS DELIVERED (EQUIVALENT FLIGHT RATE, FLTS/YR) PER MISSION (Kg)		
					$Pb\ I_2^{129}$ (1.600 Kg/YR)	Tc^{99} (3,000 Kg/YR)	CERMET (189,520 Kg/YR)
LOW LAUNCH RATE CANDIDATE SYSTEMS	SINGLE LAUNCH 1 65K STS PER MISSION	OTS-1	SL-5	5,400	700 (2)	850 (4)	550 (349)
		OTS-3	SL-7	4,900	550 (3)	700 (4)	450 (421)
		OTS-5	SL-9	11,800	2,600 (3FLTS ea. 2 YRS)	2,950 (1)	2100 (90)
	DUAL LAUNCH 2 65K STS PER MISSION	OTS-1	DL-1	14,200	3,500 (1 FLT ea.2 YRS)	3,900(4 FLTS ea.5 YRS)	2800 (68)
		OTS-4	DL-4	15,000	3,800 (1 FLT ea 2 YRS)	4250(2 FLTS ea.3YRS)	3000 (63)
REFERENCE SYSTEM	DUAL LAUNCH 1 UPRATED STS 1 SDCLV (LRB) PER MISSION	OTS-6	REF SYSTEM	30,614	7,850 (1 FLT ea.5 YRS)	8,700(1 FLT ea.3YRS)	6000 (32)

*KEY TO ORBIT TRANSFER SYSTEM CODES.	
OTS 1	SINGLE STAGE CRYOGENIC LONG LIFE OTV; EXPENDABLE
OTS 3	2 STAGE: EXPENDABLE CRYOGENIC INJECTION STAGE; STORABLE SOIS
OTS 4	2 STAGE: REUSABLE CRYOGENIC AEROBRAKED INJECTION STAGE; EXPENDABLE SOLAR ELECTRIC STAGE AS SOIS
OTS 5	SINGLE STAGE 270 Kw SOLAR ELECTRIC; EXPENDABLE
REFERENCE SYSTEM → OTS 6	2 STAGE: REUSABLE CRYOGENIC AEROBRAKED INJECTION STAGE; EXPENDABLE CRYOGENIC SOIS

Figure 2.3-3. Performance Summary for Candidate Low-Launch-Rate Systems for Alternative Waste Mixes

A comprehensive trade study would be necessary to select the optimum orbit transfer system from among these five candidates. Due to the relatively small number of missions, a comparison of life cycle costs, including DDT&E, would be needed to select the most cost-effective system.

2.4 CHARACTERISTICS OF REFERENCE SPACE SYSTEM

This section includes a summary of the rationale for selecting the reference space system and an overview of system elements and operation. More detailed information on

system elements and operation is contained in sections 6.0, 7.0, and 8.0 of Volume 2.

Reference System Selection. The reference space system was selected at a joint working-group meeting, in August of 1981, between Boeing Aerospace Company, Battelle Northwest Laboratories, Battelle Columbus Laboratories, and the Marshall Space Flight Center. The selected waste mix is the cermet high-level waste mix, with 95% of the cesium and strontium removed, as developed by Battelle Northwest Laboratories. This waste mix was the only one of the three considered that showed the potential for long-term risk reductions when compared to mined geologic repository.

The space system used to transport the reference waste mix from the launch site to the 0.85 AU heliocentric orbit destination was selected from the candidates recommended at the conclusion of the 1980 MSFC-Boeing space disposal study. The selected system combines the lowest risk with the highest performance of the recommended systems. Of the four systems recommended for further study at the end of the 1980 effort, the reference system was judged most compatible with the direction of ongoing NASA studies of future space transportation systems.

Major System Elements. Major elements of the reference space system are shown in Figure 2.4-1. They include:

1. The waste payload system, which supports and protects the waste form during ascent and orbit transfer operations.
2. The flight support system, which provides a mechanical interface between the waste payload and launch vehicle systems and which provides for mechanical transfer of the waste payload system to the orbit transfer system in LEO.
3. The launch system, which transports the waste payload and orbit transfer systems from the launch site into a 270-km-altitude low Earth orbit. The launch system is composed of two vehicles: one carries the waste payload and flight support system; the other, the orbit transfer system. The waste payload system is carried in an uprated version of the existing STS using liquid rocket boosters. The uprated STS has a payload capacity to LEO of 47,000 kg. The orbit transfer system is carried to LEO in a shuttle-derived cargo launch vehicle which replaces the winged orbiter component of the STS with an expendable cargo shroud and a reusable propulsion and avionics module. The shuttle-derived cargo launch vehicle provides increased internal volume for payload accommodation and has a payload capacity of 84,000 kg.
4. The orbit transfer system, which transports the waste payload from LEO to the destination heliocentric orbit at 0.85 AU. The orbit transfer system is composed of a reusable injection stage and an expendable SOIS. A waste payload adapter on the

front of the SOIS allows docking with the orbiter and provides mechanical support for the waste payload during orbit transfer operations.

5. Launch site facilities, which consist of a nuclear payload processing facility (NPPF), for assembly and integration of the waste payload system with the flight support system, and the facilities required for turnaround of launch vehicle systems and the reusable portion of the orbit transfer system.

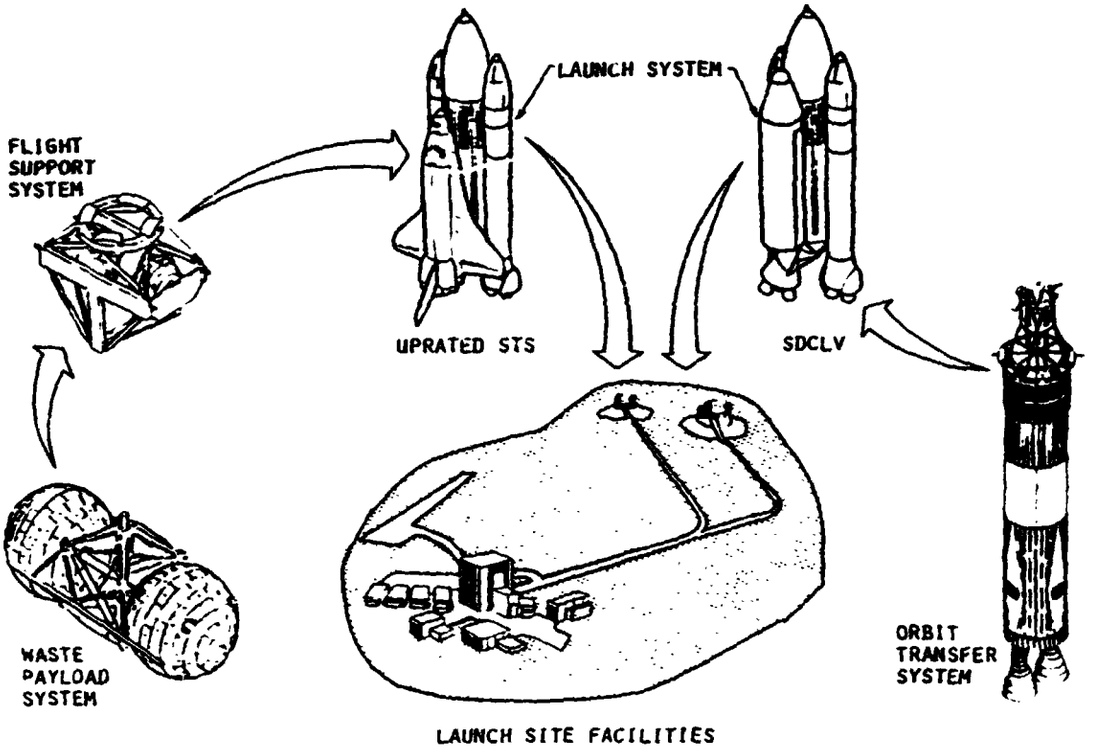

Figure 2.4-1. Reference Space System Major Elements

System Operation. Figure 2.4-2 is a schematic of key mission operations for the reference space system. Key events include:

1. Launch of the cargo launch vehicle which places the two-stage orbit transfer system into LEO.
2. Launch of the waste payload to LEO in the uprated space shuttle.
3. Rendezvous in LEO between the orbit transfer system and the orbiter.
4. Transfer of the waste payload to the orbit transfer system from the flight support system which supports it in the orbiter cargo bay. Subsequent to waste payload transfer, the orbiter waits in LEO for recovery of the first stage of the orbit transfer system.

5. Injection of the expendable SOIS into heliocentric transfer orbit by the recoverable first stage.
6. Injection (after a 165-day coast in transfer orbit) of the SOIS and the waste payload into the destination heliocentric orbit at 0.85 AU.
7. Recovery of the injection stage for reuse, following a retroburn and aerobraking maneuver which inserts it into LEO.

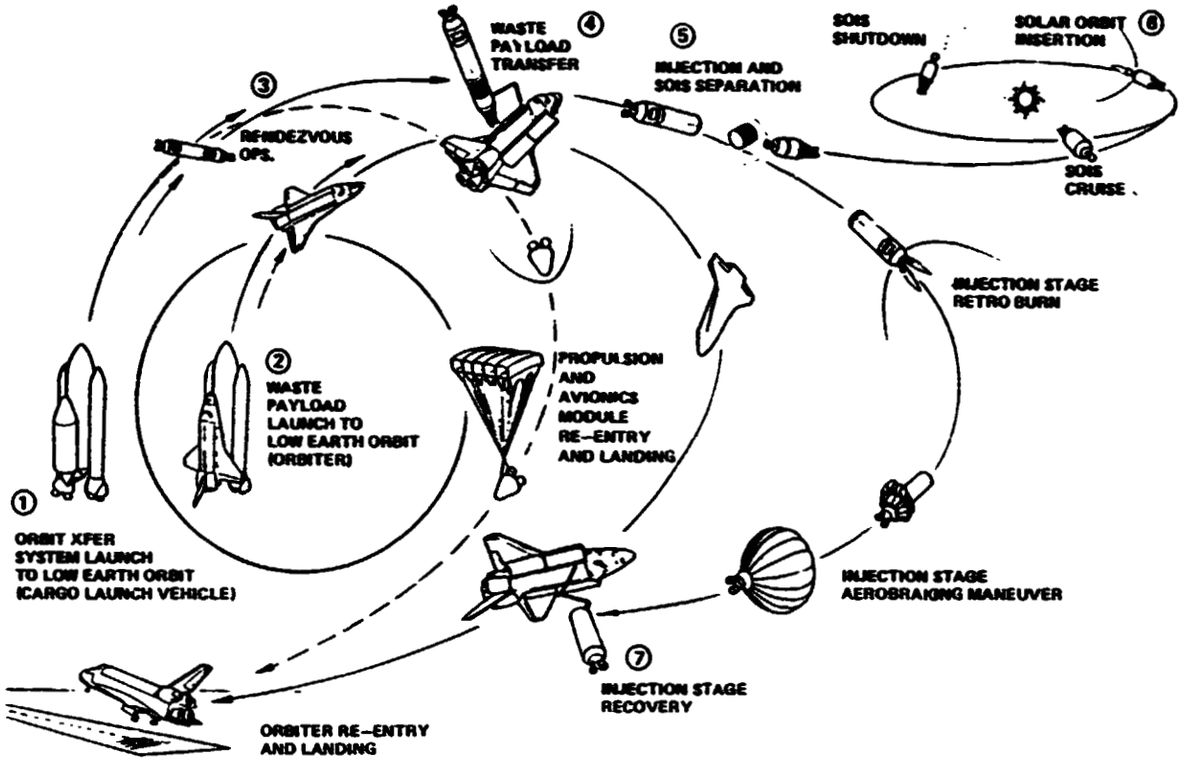

Figure 2.4-2. Reference Space System Delivery Operations Summary

3.0 MAJOR CONCLUSIONS

This section summarizes the major conclusions resulting from this study.

1. Parameters for the reference cermet waste form are available only by analogy. Detail design of the waste payload would require determination of actual waste form properties.
2. Billet configuration constraints for the cermet waste form limit waste payload packing efficiency to slightly under 75% net volume, resulting in a 20% increase in the number of flights and subsequent increases in both cost and risk.
3. Alternative systems for waste mixes requiring low launch rates (technetium 99, iodine 129) can make effective use of the existing 65K STS in either single- or dual-launch scenarios.
4. A trade study involving a comprehensive comparison of life cycle costs would be required to select the optimum orbit transfer system for low-launch-rate systems. This was not a part of the present effort due to selection of the cermet waste form as the reference for the study.
5. The reference space system offers the best combination of cost, risk, and alignment with ongoing NASA technology development for disposal of the reference cermet waste form within specified system safety guidelines.

4.0 RECOMMENDATIONS FOR FURTHER STUDY

The space system selected for this study is virtually identical to system DL-2 described in the 1980 MSFC-Boeing study. Accordingly, recommendations from this study are not specific to this effort and should be considered an amplification of those from the 1980 study. Because of the very preliminary level of definition of the reference space system, the following recommendations address generic rather than specific system issues.

1. Further analysis of the reference integral shield waste payload system, aimed at validating its ability to withstand terminal velocity impact, should be conducted as the first part of a comprehensive waste payload accident-effects analysis for this concept.
2. Because of the influence of waste form packing efficiency on waste payload mass, research should be directed at relaxing fabrication constraints on the cermet waste form in the interest of achieving better packing efficiency. A reduction of 20% to 25% could be achieved in the total number of missions for disposal of a given mass of cermet.
3. A preliminary study of the contingency rescue mission, in more detail than reported in past studies, is required to identify concepts and define risk benefits more specifically. This task will determine whether contingency rescue is an enabling capability for space disposal and, if it is, will provide a basis for the level of emphasis to be applied.
4. While the 0.85 AU heliocentric orbit destination was selected as a reference for this study, further analysis of space disposal destinations in the geolunar system should be conducted. Efforts should be aimed at defining the best geolunar destination and validating its stability to the same level as the reference 0.85 AU destination. If validated, substantial cost and risk benefits could be realized.